Anatomical Correlates for Category-Specific Naming of Objects and Actions: A Brain Stimulation Mapping Study

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Abstract: The production of object and action words can be dissociated in aphasics, yet their anatomical correlates have been difficult to distinguish in functional imaging studies. To investigate the extent to which the cortical neural networks underlying object- and action-naming processing overlap, we performed electrostimulation mapping (ESM), which is a neurosurgical mapping technique routinely used to examine language function during brain-tumor resections. Forty-one right-handed patients who had surgery for a brain tumor were asked to perform overt naming of object and action pictures under stimulation. Overall, 73 out of the 633 stimulated cortical sites (11.5%) were associated with stimulation-induced language interferences. These interference sites were very much localized (<1 cm^2), and showed substantial variability across individuals in their exact localization. Stimulation interfered with both object and action naming over 44 sites, whereas it specifically interfered with object naming over 19 sites and with action naming over 10 sites. Specific object-naming sites were mainly identified in Broca's area (Brodmann area 44/45) and the temporal cortex, whereas action-naming specific sites were mainly identified in the posterior midfrontal gyrus (Brodmann area 6/9) and Broca's area ($P = 0.003$ by the Fisher's exact test). The anatomical loci we emphasized are in line with a cortical distinction between objects and actions based on conceptual/semantic features, so the prefrontal/premotor cortex would preferentially support sensorimotor contingencies associated with actions, whereas the temporal cortex would preferentially underpin (functional) properties of objects. *Hum Brain Mapp 35:429–443, 2014.* © 2012 Wiley Periodicals, Inc.

Key words: object naming; action naming; grammatical class; semantics; conceptual knowledge; intraoperative brain mapping

INTRODUCTION

Comparisons of the processing of object and action words (nouns and verbs) in brain-injured patients and normal adults have taken on increased importance in the last few years, and may indicate at least partial neural segregation of the processes [Vigliocco et al., 2011]. Neuropsychological studies [Chen and Bates, 1998; Damasio and Tranel, 1993; Daniele et al., 1994; Shapiro et al, 2001;

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Zingeser and Berndt, 1990] have demonstrated that the production of object words (nouns) and action words (verbs) can be dissociated in aphasics, as there are patients who are more impaired in naming action pictures and using verbs, and other patients who are more impaired in naming object pictures and using nouns. Some authors showed partial anatomical segregations in the human brain between verb and noun naming [Caramazza and Hillis, 1991; Damasio and Tranel, 1993; Daniele et al., 1994; Miceli and Caramazza, 1988; Zingeser and Berndt, 1990]. They suggested the left frontal cortex could be particularly involved in the process of naming actions, while the left temporal lobe seems more crucial for the process of naming objects.

However, functional neuroimaging (PET, fMRI) [Perani et al., 1999; Saccuman et al., 2006; Siri et al., 2008; Tyler et al., 2001] and repetitive transcranial magnetic stimulation (rTMS) studies [Cappa et al., 2002; Shapiro et al., 2001] in healthy individuals have given more variable results. Overall there is a trend to greater activation for verbs relative to nouns in the left posterior middle temporal gyrus and the left inferior frontal gyrus (LIFC) in a significant number of PET and fMRI studies [Bedny et al., 2008; Davis et al., 2004; Fiez et al., 1996; Kable et al., 2002; Perani et al., 1999; Shapiro et al., 2005, 2006; Tranel et al., 2005; Tyler et al., 2004; Warburton et al., 1996; Yokoyama et al., 2006], while greater activation associated with nouns in the left inferior temporal regions has been revealed by fewer fMRI studies [Shapiro et al., 2005, 2006]. In addition, major implication of frontal regions has been observed in the action-processing investigations conducted using rTMS [Shapiro et al., 2001, Cappa et al., 2002, Lo Gerfo et al., 2008, Crepaldi et al., 2011].

Since, there is clearly a great deal of inconsistency in the evidence described above, the anatomical correlates for category-specific naming of objects and actions remains imperfectly known and the nature of this distinction is not well understood [Crepaldi et al., 2011; Vigliocco et al., 2011]). It has been argued that the lexical and conceptual knowledge of actions could be mediated by a left-lateralized "action-property-based" network, which would include the IFG, the central region, the SMG, the pMTG, and posterior ventral temporal areas [Kemmerer and Gonzalez-Castillo, 2010; Péran et al., 2010]. Interestingly, Campanella et al. [2010], who investigated temporal lobe tumor patients, pointed out the posterior middle temporal gyrus as the area the most critically associated with naming deficit for manipulable objects. Previously, Tranel et al. [2001] found that the left IFG was the region of maximal lesion overlap in patients with impaired naming of actions. Another frontal region was also strongly linked with impairment on action naming: the lateral precentral gyrus and the rostrally adjacent posterior middle frontal gyrus [Kemmerer Gonzalez-Castillo, 2010]. Again, this particular region tends to be activated during the processing of tools and manipulable objects in functional imaging [Gerlach et al., 2002]. Moreover, different types of manipulability (i.e., functional manipulability –e.g., "saw" as opposed to volumetric manipulability –e.g., "table") could elicit different patterns of activation [Rueschemeyer et al., 2010].

Electrostimulation mapping (ESM) is an invasive inhibition technique used to map essential language areas in epilepsy and brain tumor surgery [Berger, 1996; Haglund et al., 1994; Ojemann et al., 1989]. It directly interacts with the functioning of the neural structures required for a task, eliciting language disturbances under stimulation. This technique has already been successfully used to distinguish category-specific brain representations for tools and animals [Ilmberger et al., 2002], nonliving and living stimuli [Giussani et al., 2011; Papagno et al., 2011], or discrete cortical regions associated with object attributes like knowledge of color [Roux et al., 2006]. Previous ESM experiment from Corina et al. [2005] showed that errors in action naming were preferentially associated with the stimulation of the SMG, and the posterior middle temporal gyrus. However, very few frontal sites were stimulated in this study. The aim of the present experiment was to disentangle cortical areas necessary to name object words (nouns) and action words (verbs), particularly within the aforementioned "action/manipulation-property-based" neural substrates.

Abbreviations	
ESM	electrostimulation mapping
fMRI	functional magnetic resonance imaging
IFG	inferior frontal gyrus
MFG	middle frontal gyrus
PET	positron emission tomography
SFG	superior frontal gyrus
WHO	world health organization

METHODS

Patients

From January 2007 to October 2010, 41 patients with brain tumors (21 women; range: from 13- to 77–years-old; median age: 42 years) were prospectively studied using the awake craniotomy technique for brain mapping [Ojemann et al., 1989] in the left hemisphere. No patient had symptoms of raised intracranial pressure or intractable epilepsy. The patients' data are summarized in Table I. All of them and their families gave their informed consent for the study of their functional areas by direct brain mapping. The ad hoc Consultative Committee of INSERM (*Institut National de la Santé et de la Recherche Médicale*) gave its approval for the storage of patients' data and the protection of their anonymity.

Preoperative Language Testing

Language dominance evaluation [Oldfield, 1971] and preoperative language examinations were conducted by our

TABLE I. Population characteristics

Patient population characteristics (n=41)	
Age – years	
Median	42
Range	13 – 77
Sex – no. (%)	
Male	20 (48.8%)
Female	21 (51.2%)
Preoperative language assessment – no. (%)	
No deficit	31 (75.6%)
Slight aphasia	10 (24.4%)
Tumor location – no. (%)	
Inferior frontal gyrus	11 (26.8)
Middle frontal gyrus	10 (24.4)
Superior frontal gyrus	11 (26.8)
Central region (pre- and post-central gyri)	5 (12.2%)
Temporal lobe	4 (9.8%)
Pathological findings – no. (%)	
Grade II glioma	20 (48.8%)
Grade III glioma	3 (7.3%)
Glioblastoma	4 (9.8%)
Pleomorphic xanthoastrocytoma	1 (2.4%)
Anaplastic ependymoma	1 (2.4%)
Ganglioglioma	1 (2.4%)
Metastasis	4 (9.8%)
Cavernoma	3 (7.3%)
Meningioma	2 (4.9%)
Gliosis	2 (4.9%)
Follow up — months	
Median	11.6
Range	0.3 – 44.9

speech therapist team to rule out any language-specific deficits. This testing included an evaluation of written and auditory comprehension (word– and sentence–picture matching tests, object manipulation upon oral instruction), visual naming, language fluency, reading, dictation, repetition, written transcription, and object manipulation. These tests that have been used for many years by the speech therapists and neurologists of our institution who are specialized in aphasic disorders, were standardized for all the patients [Roux et al., 2004; Roux et al., 2008]. Patients with significant preoperative language defect or object/action naming dissociations were excluded from this study. No patient who was included had anomic aphasia (i.e., >10% errors in naming tests).

All patients resulted right-handed according to the Edinburgh Handedness Inventory Score [Oldfield, 1971]. They were French natives. Their language examinations were normal except for 10 patients who presented slight aphasic troubles (i.e., they made errors in the preoperative naming test, though more than 90% of the items were correctly named).

Stimuli and Experimental Design

The stimuli used in the action/object picture-naming task were taken from the Center for Research in Language-International Picture Naming Project corpus CRL-IPNP [Szekely et al., 2005]. We used a subset of 80 items from the original corpus (see Appendix). These were 40 objects and 40 actions. Stimuli were selected during the preoperative language examination, but were not matched (e.g., frequency, familiarity, length, age of acquisition, familiarity, or visual complexity for actions were not matched with the same variables for objects). The majority of the items we used involved manipulability. Most were nonhomonymous (nouns or verbs).

During surgery, black, and white drawings of common objects and actions, which were correctly named without any latency during the preoperative language examination, were presented to the patient. Patients performed overt object naming from object images, and overt action naming from action images. They were asked to produce nouns and verbs in the context of short phrases or sentences, like "*this is a scissor*" and "*he cuts.*" This production task was constructed to rule out grammatical ambiguities between nouns and verbs [Shapiro et al., 2006]. Although static drawings do have their limitations to explore action-naming performance [den Ouden et al., 2009], they have been widely used in neuropsychological and psycholinguistic studies (see Mätzig et al., 2009 for review).

Stimulation Mapping

The patients were all operated on during an awake craniotomy. We used a neuronavigational system (Medtronic®, Tolochenaz, Switzerland) to localize the tumor, and to guide the mapping procedure in all patients. Intraoperative cortical stimulation was used to localize functional cortex after determination of the after discharge threshold by electrocorticography. The cortex was directly stimulated, using the bipolar electrode of the NIMBUS® Multifunctional Stimulator (1 mm electrodes separated by 5 mm–Newmedic®, Toulouse, France). The current amplitude was progressively increased by 1 mA, beginning at 1mA. We used biphasic square-wave pulses of 1 ms at 60 Hz, with maximum train duration of 4 s. The white matter was also directly stimulated, alternating with brain tumor resection. Nevertheless, because of time constraints, we only used the object-naming task for subcortical mapping.

Each patient participated in object- and action-naming tasks for each stimulated site. When we started a direct cortical stimulation procedure, we chose a substantial number of sites on the brain surface. For each patient, we stimulated the same areas during the entire procedure to test for the 2 tasks. The number of sites studied was variable and depended on the size of the craniotomy. The stimulation was applied just before picture display. Object brain mapping was completed first, followed by action mapping. Picture presentation without stimulation was randomly performed in both conditions (object and action naming), so that the patient was never informed when the brain was stimulated ("single-blind experiment"). Naming interferences we detected were classified in six types, which are described in Table II.

TABLE II. Types of interferences induced by stimulation mapping

	Patient response to stimulation	
Type of interference	Description	Example
Speech arrest	No utterance is produced at all (i.e., neither the object/action name nor the carrier phrase "This is . . . /He . . . ").	-
Anomia	The object/action name is not produced but the carrier phrase is.	"This is . . . well, I know it..it's a . . . " "He . . . I know what he's doing . . . "
Semantic paraphasia	The patient substitutes a semantically related or associated word for the target word.	"Fruit" for "pear" "The dog shouts" for "The dog barks"
Phonological paraphasia	The patient produces unintended phonemic epenthesis, omission, substitution, metathesis, and/or repetition.	"Aligigator" for "alligator" "He juddles' for "He juggles"
Neologism	The patient produces form-based errors that are "possible but nonexistent words".	"Horp" for "apple" "She derks" for "She fishes"
Hesitation	The object/action name is correctly produced, but only after a marked delay.	" . . . ..ar..tich.oke . . . " " . . . she . . . squezzes"

Conditions of Validation

Functional language areas were identified by errors in object and action naming during stimulation mapping. To be accepted as positive sites, the language sites found were meticulously tested three times. The same type of interference had to be produced 3/3 times. Those showing no reproducible language interference were not included in the statistical analysis.

Mapping procedures were video-recorded as evidence of each patient's cortical organization and so that the patient's responses could be further analyzed in team meetings. Patients' oral answers were recorded by a microphone, which was placed near the mouth. Intraoperative photographs of the brain were taken with the sites of positive cortical stimulation. After each case analysis, the site of speech arrest was prospectively entered into an excel sheet database. Finally, it must be emphasized that we qualified a site *specific* for "object" or "action" when no other language interference was found in that site during these naming tasks. However, we cannot completely exclude the possibility that other functions not tested in this study could be revealed by stimulation in a "specific" site. Therefore, the task specificity of an interference site could be inversely related to the number of tasks administered.

Statistical Analysis

Throughout this study, all data regarding brain-mapping results were integrated into an Excel database (Microsoft Corp.) by the senior neurosurgeon (Franck-Emmanuel Roux). In presenting our data, we referred to the classification system he adopted, which is based on gyral/sulcal anatomy. Fifteen regions were defined for the left hemisphere. For example, the supramarginal gyrus was considered a region, whereas large temporal gyri (e.g., the superior temporal gyrus) are arbitrarily divided into three segments (anterior, middle, and posterior) by drawing imaginary lines prolonging the pre- and postcentral sulci inferiorly. Additionally, an imaginary line prolonging the anterior ascending ramus of the Sylvian fissure superiorly separates the middle and the posterior segments of the middle frontal gyrus. This line usually stands 2 cm in front of the precentral sulcus. Sites were localized through the use of preoperative MR imaging integrated in neuronavigation system (Medtronic, Tolochenaz, Switzerland) in conjunction with intraoperative photographs, films, and surgeon notes. Data were then stored in the excel database. To analyze brain-mapping data, interference sites were classified in three categories: 1 – specific object naming site; 2 – specific action naming; and 3 – common site of interference.

To address the question of the anatomical segregation of naming categories for actions and objects within the cerebral cortex, we analyzed the group data considering six functional anatomical regions: the superior frontal gyrus, the middle midfrontal gyrus—mostly representing BA46/9, the posterior midfrontal gyrus—mostly representing BA9/6/4, Broca's area—encompassing the pars opercularis and the pars triangularis and referring to BA44/45, the left temporal lobe (which was considered as a single unit, since few patients were operated on for temporal lesions in this study) and the supramarginal gyrus. Those regions were determined by taking into account their anatomo-functional homogeneity, their hypothetical role in naming objects and actions [Cappa and Perani, 2003; Shapiro et al., 2005; Cappelletti et al., 2008], and the technical limitations due to the sample size and the exposed surface of cortex in our patients. The classification system and the anatomical regions used in the present study are shown in Figure 1.

Categorical variables were reported by frequencies and percentages. To compare the percentages of specific areas per task, we used each stimulation site as a statistical unit. Comparisons between groups were performed using Pearson's χ^2 test or Fisher's exact if applicable. All *P*-values reported were two-sided. For all statistical tests, the differences were considered significant at the 5% level. Statistical analyses were performed using the STATA 11.0 software.

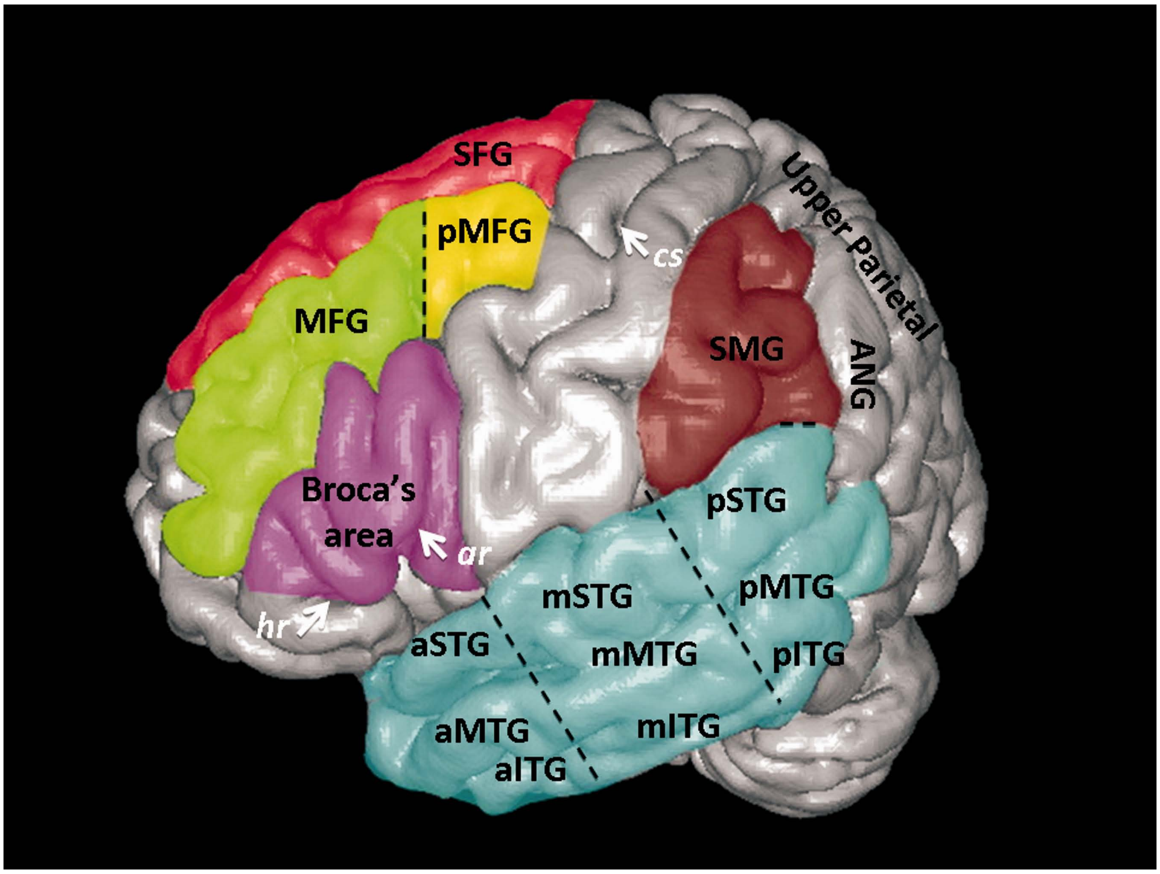

Figure 1.

This classification system is based on gyral/sulcal anatomy: SFG, superior frontal gyrus; MFG, middle frontal gyrus; pMFG, posterior segment of the middle frontal gyrus; IFG, inferior frontal gyrus; STG, superior temporal gyrus; MTG, middle temporal gyrus; ITG, inferior temporal gyrus; SMG, supramarginal gyrus. The prefixe a,m,p are respectively used to mark out the anterior, middle, and posterior segments of the temporal gyri (e.g., aSTG corresponds to the anterior segment of the superior temporal gyrus). CS: central sulcus; ar: ascending ramus; hr: horizontal ramus of the lateral sulcus. The six functional anatomical regions we considered to address the question of the anatomical segregation of naming categories for actions and objects are outlined in colors: the SFG (red); the mMFG (green); the pMFG (yellow); Broca's area (i.e., the pars opercularis and the pars triangularis) (purple); the temporal lobe (blue); and, the SMG (brown). [Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com.]

RESULTS

Overall Results

Figure 2 summarizes the distribution of cortical sites studied for each region and the results of stimulation mapping.

Cumulatively, 633 cortical sites were stimulated over the left hemisphere of our 41 patients. The 543 frontal sites were distributed as follows: 181 in the inferior frontal gyrus, 232 in the midfrontal gyrus, and 130 in the superior frontal gyrus. Brain tumor location and cortical exposure also allowed us to study 76 sites in the temporal lobe and 14 sites in the parietal lobe (supramarginal gyrus). Current intensity necessary to elicit these interference sites ranged from 2 to 5.5 mA. No generalized seizure occurred during surgery, and no intraoperative complication was noted in this series.

We found 73 positive naming sites localized in small cortical areas (<1 cm^2). Stimulation interfered with both object and action naming over 44 sites (common sites), whereas it only interfered with object naming over 19 sites (specific object naming sites) and with action naming over 10 sites (specific action naming sites).

The regional relative error rates for object-specific, action-specific, and common object and action sites, show that the entire perisylvian cortex was involved in object and action naming. However, the frontal cortex was globally more affected by stimulations during the naming of actions (e.g., maximum relative error-ratio in the frontal lobe for specific action naming: 31% in the middle frontal gyrus, 11% in the superior frontal gyrus, and 9% in the inferior frontal gyrus), whereas the temporal cortex was more affected by stimulations during the naming of objects

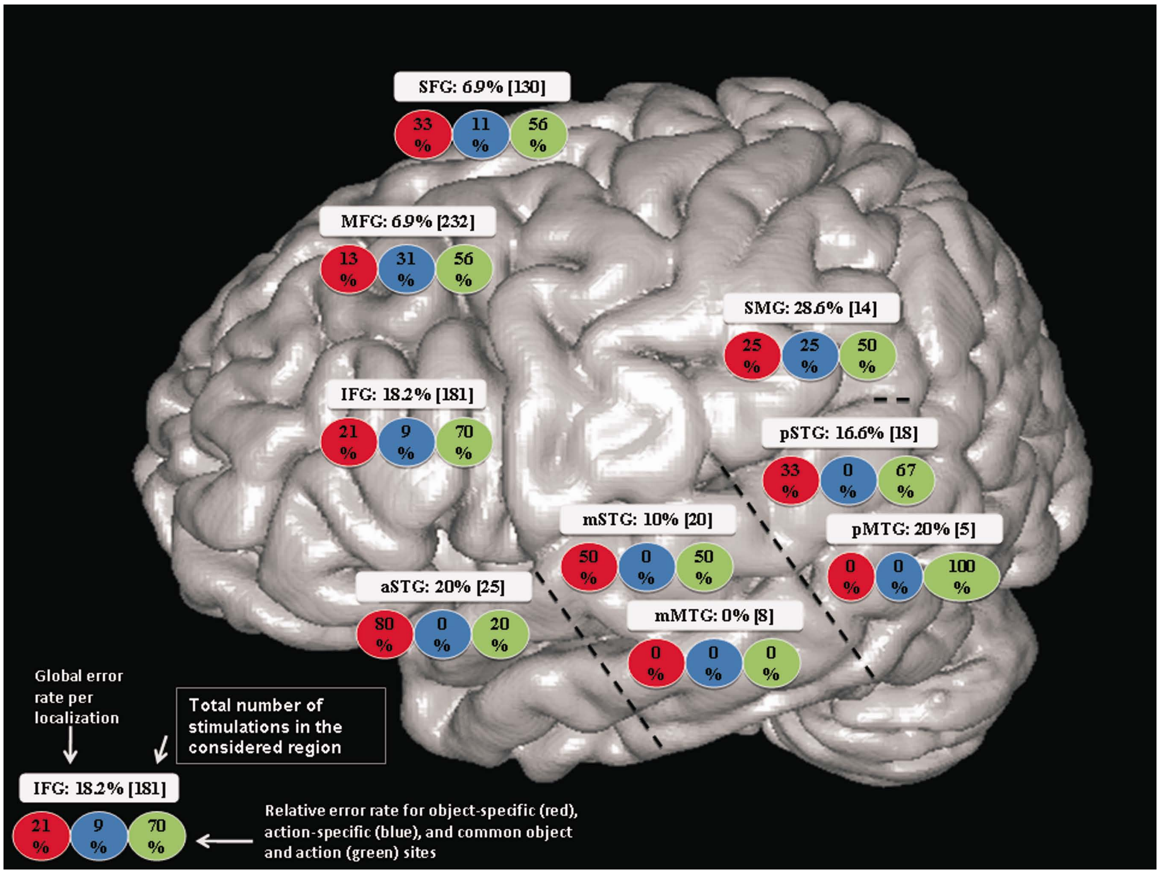

Figure 2.

Localization of the naming errors induced by ESM. Cortical regions indicating the number of stimulations performed in the considered region, and overall error ratio (blue box). The percentages of stimulations that elicited object-specific (red circle), action-specific (blue circle), and common object- and action-naming (green circle) interferences are also indicated for each region studied. [Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com.]

(e.g., maximum relative error-ratio in the temporal lobe for specific object naming: 80% in the anterior segment of the superior temporal gyrus [SFG], 50% in the middle segment of the SFG, and 33% in the posterior segment of the SFG).

Stimulation in the regions of the parietal cortex (supramarginal gyrus) gave rise to a balanced pattern, since the relative error-ratio rate for object-specific, action specific, and common sites were 25, 25, and 50%, respectively.

Individual Results

The number of positive interference sites per patient ranged from 0 to 6 (median: 2), and a total of 32 patients (78%) had positive stimulation maps (at least one interference site), whereas 9 patients (22%) had negative maps (no interference site). Among the 32 patients who had positive maps during the object- and action-naming tasks, three patterns of disruption were distinguished:

1. Strictly identical maps: all interference sites were common sites. This pattern was observed in 18 patients.
2. Partially overlapping maps: common but also object and/or action naming selective interference sites were found. This pattern was observed in 10 patients.
3. Nonoverlapping maps: all interference sites were selective either for object- or action naming (complete segregation). This pattern was observed in four patients, who demonstrated specific object naming (2 patients), or specific action naming (1 patient), or both specific object and specific action naming sites (1 patient).

Consequently, at least partial segregation of object and action naming sites was observed in 14/41 patients (34%), with anatomically distinct interference sites giving rise to specific errors in action or object naming. Notably, there was only one patient who demonstrated a double dissociation (i.e., one site showed a significant interference in object naming with sparing of action naming and another showed the reverse pattern with a significant interference in action naming with sparing of object naming). An illustrative case of partial segregation is shown in Figure 3.

Specific Results

Anatomical distribution of interferences

As stimulation mapping demonstrated differences in the regional error-ratio rates for object-specific and action-specific interference sites, we tested the distribution of these specific interference sites considering six functional regions by using the Fisher's exact test (Table III).

i) Cerebral regions associated with specific object naming interferences
Compared with no-interference sites, and common or specific action-naming interference sites, the specific object-naming interference sites were mainly identified in Broca's area (7/19, 37%) and the left temporal lobe (6/19, 32%), and to a lesser extent in the superior frontal gyrus (3/19, 16%), the middle midfrontal gyrus (1/19, 5%), the posterior midfrontal gyrus (1/19, 5%), and the SMG (1/19, 5%) (P 0.003).

ii) Cerebral regions associated with specific action naming interferences
Compared with no-interference sites, and common or specific object-naming interference sites, the specific action-naming interference sites were mainly identified in the posterior midfrontal gyrus (4/10, 40%) and Broca's area (3/10, 30%), and to a lesser extent in the middle midfrontal gyrus (1/10, 10%), the SFG (1/10, 10%), and the SMG (1/10, 10%) (P 0.003).

The association between these two classifications of categorical data (specific interferences and anatomical distribution) reached significance ($P = 0.003$). What emerges from this analysis is that, whereas the posterior midfrontal gyrus was more specifically implicated in the process of actions and the temporal lobe in the process of objects, Broca area was largely implicated in the process of both objects and actions. These findings are illustrated by an example shown in Figure 4.

Types of interferences

Stimulation mapping elicited different types of errors during the object- and the action-naming tasks. The most frequently observed errors were anomia (33%) and speech arrest (32%). Less frequent errors included phonemic paraphasias, and semantic paraphasias, neologisms, and hesitations. Speech arrest, anomia, and neologism essentially occurred after stimulation of the inferior frontal cortex (53/56, 95%), whereas phonemic paraphasias were mainly elicited in the supramarginal gyrus (6/6, 100%). All error types and their anatomical distribution are reported in Table IV. The association between the cortical site of stimulation and the type of disruption induced was significant for both object and action naming ($P < 0.001$ by the Fishers's exact test). Error patterns were very similar across tasks.

DISCUSSION

In this study, we used stimulation mapping to explore the anatomical correlates for object- and action-naming processing in the left dominant hemisphere. Our experimental results favor the hypothesis that the systems required for retrieving words denoting objects and actions are partially segregated. Some areas whose stimulation gave rise to naming interference for both types of stimuli are likely involved in a distributed language network supporting output lexicon irrespective of the object/action distinction. However, our study brought up also areas that, though less frequent, are specifically involved in each of these types of word classes, either object- or action-related. In addition, stimulations of the posterior midfrontal gyrus yielded significantly more interference in the action-naming task, whereas stimulation of the left temporal lobe revealed significantly more errors when using an object-naming task.

Our data go along the same line as those reported by the team of Seattle [Corina et al., 2005; Ojemann et al., 2002] who compared a verb generation task to an object-naming task [Ojemann et al., 2002] or directly compared object and action naming [Corina et al., 2005]. They provided strong support for partial segregation in the cortical representation of object- and action-words. Ojemann and coworkers [Ojemann et al., 2002, Corina et al., 2005] laid stress on temporal-parietal action-word specific areas (i.e., in the posterior part of the medial and upper temporal gyrus and in the supramarginal gyrus), while they highlighted an important role of temporal areas in retrieving object names (i.e., the left anterior superior temporal cortex and the left middle temporal gyrus). Our results confirm the previously described data in those stimulation series, that suggest there is a preferred dorsal system comprising the temporal-parietal cortex and the prefrontal/anterior premotor region, that processes action words, and another preferred ventral system involving anterior and middle portions of the temporal lobe, that processes object words.

In the following sections, we will discuss clinical and research studies addressing neural representation of object and action naming in the context of brain-damaged patients and healthy subjects.

Neural Models of Object Words (Nouns) and Action Words (Verbs) Processing

Double dissociation, between aphasic patients who were more severely impaired in producing nouns than verbs and patients who showed the opposite pattern (greater

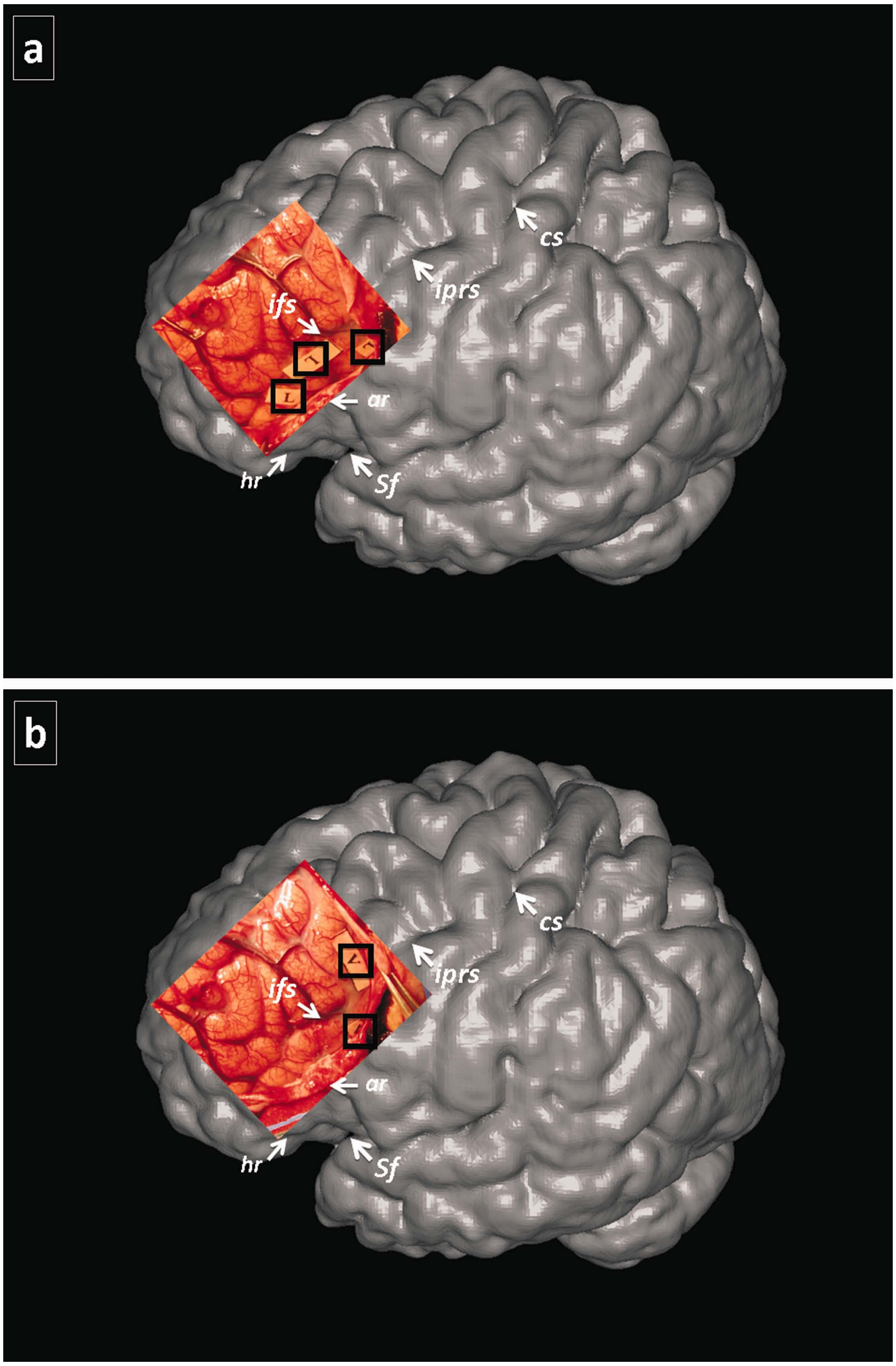

Figure 3.

Illustrative case. A 40-year-old right-handed woman underwent left frontal craniotomy for a WHO-grade-II glioma. Preoperatively, language testing revealed no language deficit. Intraoperative photographs of the cortical mappings are superimposed to a left lateral view of the patient's brain: (**a**) Black boxes around letter "L" depict object-naming interference sites ($n = 3$), which were found in the pars opercularis ($n = 2$) and pars triangularis ($n = 1$)—i.e. the Broca area. (**b**) Black boxes around letter "V" depict action naming interference sites ($n = 2$), which were found in the pars opercularis and the posterior midfrontal gyrus. CS, central sulcus; Sf, Sylvian fissure; hr, horizontal ramus of the sylvian fissure; ar, ascending ramus of the sylvian fissure; ifs, inferior frontal sulcus; iprs, inferior precentral sulcus. In this patient, we found one common (object- and action-) naming site and two object-specific sites in the Broca area, and one action-specific site in the posterior midfrontal gyrus. Cortical sites producing no language impairment were not labeled in order to improve the understanding of the intraoperative picture. [Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com.]

TABLE III. Specific naming interferences

	Specific object-naming interferences (n = 19)		Specific action-naming interferences (n = 10)	
	No.	Percentage	No.	Percentage
Functional region studied				
Superior frontal gyrus	3/19	16%	1/10	10%
Posterior midfrontal gyrus	1/19	5%	**4/10**	**40%**
Middle midfrontal gyrus	1/19	5%	1/10	10%
Broca's area	**7/19**	**37%**	**3/10**	**30%**
Temporal lobe	**6/19**	**32%**	0/10	0%
Supramarginal gyrus	1/19	5%	1/10	10%

impairment with verbs than nouns), has repeatedly been reported for the 18th century [Linnaeus, 1745; Mätzig et al., 2009; Miceli and Caramazza, 1988; Miceli et al., 1984; Vico, 1744;Zingeser and Berndt, 1988]. It provides good basic evidence that distinct functional brain mechanisms are involved in producing words of each grammatical category.

In a review conducted by Vigliocco et al. [2011], the authors sketched three main neural models that have been put forward in literature. These models consider various degrees of segregation between nouns and verbs. In a first view, mostly based on neuropsychological and electrophysiological data [Damasio and Tranel, 1993; McCarthy and Warrington, 1985; Pulvermüller et al., 1999], nouns and verbs would be represented in at least partially separable neural networks, with noun processing engaging left temporal areas and verb processing engaging left inferior frontal areas [e.g., Damasio and Tranel, 1993; Daniele et al., 1994]. The networks engaged by processing words from different conceptual domains (objects and actions) would further be fractionated to distinguish the grammatical class of words. In an alternative view, supported by functional imaging experiments [Shapiro et al., 2005, 2006], the noun–verb distinction would rather rely on the different morpho-syntactic processes that specifically apply to nouns and verbs computed in partially separated networks [Caramazza and Hillis, 1991; Miceli et al., 1984; Shapiro et al., 2000], with left temporal (including fusiform) areas engaged in integrating nouns into phrases and left inferior and middle frontal areas specifically engaged in integrating verbs into phrases. However, one cannot rule out that neural segregability may be assumed in terms of actions versus objects effect regardless of their grammatical class [Liljeström et al., 2008, 2009]. The same shared-neural network would be engaged in integration processes for both nouns and verbs, and the extent to which such a network would be engaged would instead depend upon the processing complexity and/or the selection demands of the task [Siri et al., 2008] or by the types of morpho-syntactic processes [Tyler et al., 2008].

What Are the Functional Bases of Object and Action Word Dissociation?

Cappa and Perani [2003], on the basis of a literature review, suggested the difference in the cerebral correlates of the processing of object nouns and action verbs could hardly be reduced to a strict "grammatical class" effect, but would rather be based on a continuum of differences at the phonological, conceptual/semantic, and syntactic levels [Black and Chiat, 2002]. Noun- versus verb-specific impairments have indeed been reported to arise at a lexical-phonological [e.g., Rapp and Caramazza, 2002], lexical-syntactic [e.g., Crepaldi et al., 2006], semantic [e.g., Bird et al., 2000], and syntactic level [e.g., Friedmann 2000].

A possible explanation for these patterns may be a selective loss of word class information at the level of the central semantic system (i.e., a category-specific semantic deficit) [Chao and Martin, 2000; Daniele et al., 1994; McCarthy and Warrington, 1985]. This interpretation is supported by lesion [Damasio and Tranel, 1993; Daniele et al., 1994; Miceli and Caramazza, 1988; Thompson-Schill et al., 1998; Zingeser and Berndt, 1988], TMS [Cappa et al., 2002], imaging [Chao and Martin, 2000; Fiez et al., 1996; Grabowski et al., 1998; Martin et al., 1995; Perani et al., 1999; Saccuman et al., 2006; Sahin et al., 2006; Warburton et al., 1996] and ESM studies [Giussani et al., 2009, 2011] that clearly converge in indicating the importance of left temporal cortices in object naming and in representing object knowledge, and the importance of prefrontal cortex in action naming and action knowledge. It is noteworthy, that semantic paraphasias were the prevalent naming interferences in the temporal lobe. They were mostly elicited in superior temporal areas (the anterior, middle, and posterior portions of the STG), but also in the inferior frontal cortex. These data are in line with previous stimulation mapping studies [Corina et al., 2010; Duffau et al., 2005b], which highlighted the role of two essential cortical epicenters in semantic processing: the superior and posterior temporal areas and the orbitofrontal and dorsolateral prefrontal regions. They also fit well with imaging studies [Vigneau et al., 2006], which consider two parallel networks involved in language processing. In a first one, inferior parietal (angular gyrus) and posterior temporal areas connected to the orbital part of the inferior frontal cortex by the inferior longitudinal fasciculus and the uncinate fasciculus would sustain overall meaning ; while, in a second parallel one, inferior parietal areas connected to the opercular part of the inferior frontal cortex by the arcuate fasciculus would maintain working memory.

An alternative explanation is supported by neuropsychological studies [Shapiro and Caramazza, 2003], TMS [Shapiro et al., 2001] and PET [Shapiro et al., 2005] experiments, in which nouns and verbs would be processed by a common cortical network with additional category-sensitive processes relying on the left prefrontal cortex (for verbs) - particularly the portion of the left middle frontal gyrus anterior and superior to Broca area, and bilateral

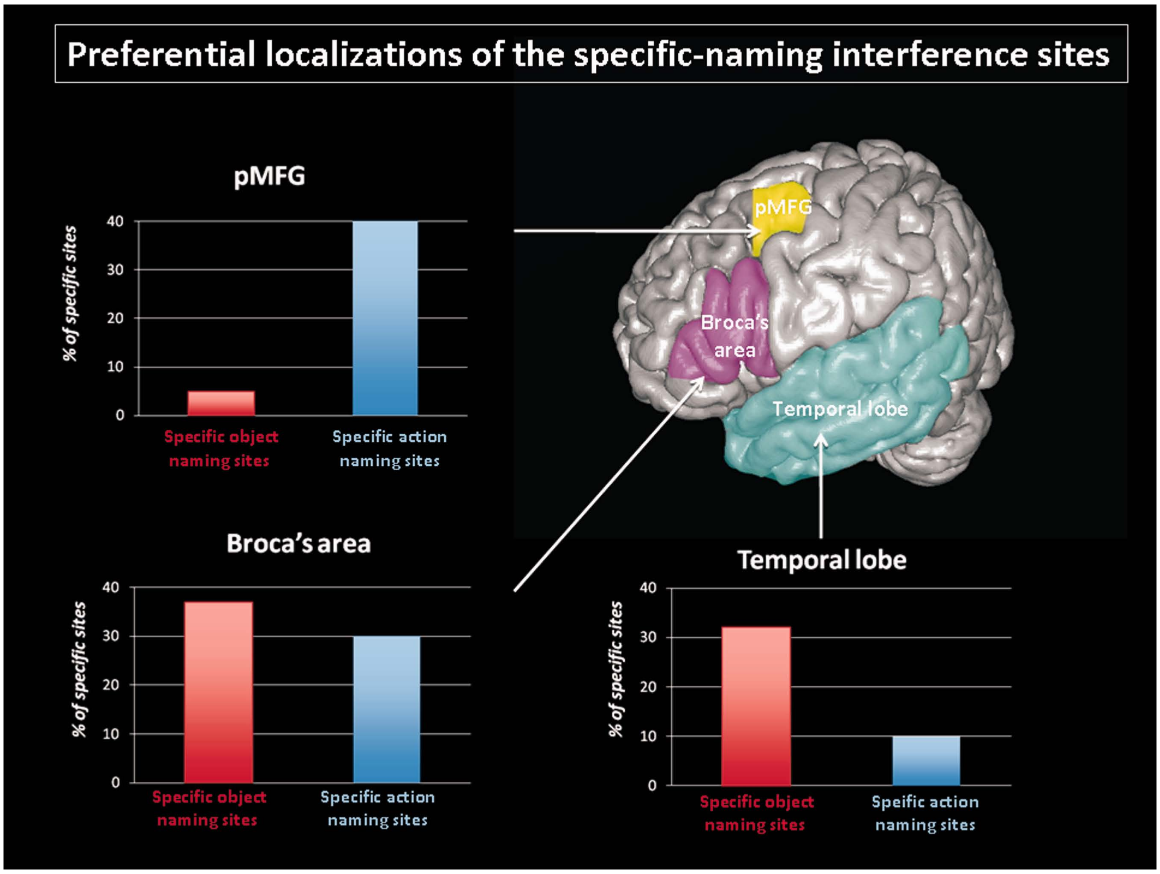

Figure 4.

Regional distribution of the category-specific naming sites as elicited by ESM. The specific object-naming interference sites were preferentially localized in the Broca area and the temporal lobe, whereas the specific action-naming interference sites were mainly localized in the posterior middle frontal gyrus and the Broca area. This association reached significance ($P = 0.003$ by the Fisher's exact test). [Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com.]

TABLE IV. Distribution of error-ratios for object and action naming disruptions

	Speech arrest		Anomia		Phonemic paraphasia		Semantic paraphasia		Neologism		Hesitation	
	Object naming	Action naming	Object naming	Action naming	Object naming	Action naming	Object naming	Action naming	Object naming	Action naming	Object naming	Action naming
IFG	12/30	11/26	10/30	10/26	0/30	0/26	1/30	0/26	5/30	5/26	2/30	0/26
MFG	5/11	5/14	5/11	5/14	0/11	0/14	1/11	2/14	0/11	0/14	0/11	2/14
SFG	2/8	2/6	3/8	2/6	0/8	0/6	0/8	0/6	0/8	0/6	3/8	2/6
aSTG	0/5	0/1	2/5	0/1	1/5	0/1	2/5	0/1	0/5	0/1	0/5	1/1
mSTG	0/2	0/1	1/2	0/1	0/2	0/1	1/2	1/1	0/2	0/1	0/2	0/1
pSTG	0/3	0/2	1/3	0/2	1/3	1/2	1/3	1/2	0/3	0/2	0/3	0/2
pMTG	0/1	0/1	0/1	0/1	1/1	1/1	0/1	0/1	0/1	0/1	0/1	0/1
SMG	0/3	0/3	0/3	0/3	3/3	3/3	0/3	0/3	0/3	0/3	0/3	0/3

For this individual data analysis, the lateral surface of cortex was divided into units based on the system adopted by the senior author and sketched in Figure 1. IFG, inferior frontal gyrus; MFG, midfrontal gyrus; SFG, superior frontal gyrus; STG, superior temporal gyrus, (a, m, p) (anterior, middle, posterior) segments, respectively; pMTG, posterior middle temporal gyrus; SMG, supramarginal gyrus.

temporal cortices (for nouns), implicated in morpho-syntactic processing. Nonetheless, comprehensive reviews [Crepaldi et al., 2011; Vigliocco et al., 2011] give evidence that a common neural system comprising the left IFG (but not limited to Broca region) is engaged in the grammatical (morphosyntactic) processing of nouns and verbs.

We found both action-specific and object-specific sites in the LIFC, a finding that is at odd with the hypothesis of (partially) separable networks and especially in this area where verb specificity would have been expected. However, the functional bases of relative action and object impairment in the LIFC are controversial. Some authors observed verb-specific activations in this region using fMRI [Perani et al., 1999; Tyler et al., 2004], whereas others failed to replicate this result and found instead noun-specific activations [Siri et al., 2008]. Siri et al. [2008] suggested that nouns and verbs differences emerge as a consequence of increasing linguistic and/or general processing demand when grammatical and semantic factors are controlled. Moreover, no significant verb-specific interference effect was found after the stimulation of Broca's area by TMS [Cappelletti et al., 2008]. Furthermore, Sahin et al. [2006], using fine-grained intra-cranial electrophysiology (ICE) in epilepsy patients, found evidence for lexical, syntactic, and phonological processing in quite a restricted territory of Broca's area (BA 45) and at different time windows after the presentation of the stimulus, but the neuro-functional signal reflecting these cognitive steps was similar for nouns and verbs.

In Crepaldi et al.'s [2011] recent review on the effect of grammatical-class on cortical representation of nouns and verbs, no frontal area was specifically associated with verbs, or was any temporal area specifically associated with nouns. Those authors concluded that "grammatical-class specific circuits may not cluster into separate brain areas; rather, they may be dispersed in different parts of the brain and be interleaved with neural structures that are shared by nouns and verbs and that also sub-serve other cognitive functions" [Crepaldi et al., 2011]. Notwithstanding, there were neural sites, which when stimulated, hindered either noun or verb lexical retrieval in all the regions of the fronto-temporo-parietal network engaged in the picture naming process (see Corina et al. [2005] and present study), thus potentially reflecting partial segregation based on grammatical-class.

In retrospect, in our study, there are a number of potential limitations, which must be acknowledged. Above all, our patient's population is heterogeneous in terms of tumor locations and tumor types. Consequently, reorganization presumably varies between individuals and has to be considered in the interpretation of the data. In particular, as opposed to metastasis and glioblastoma, the progression of grade II gliomas (GIIG) is supposed to trigger a large functional reorganization within cerebral structures (e.g., the perilesional reorganization of the language areas of GIIG located in the Broca's area, has been mainly found within the ventral premotor cortex, the pars orbitaris of the inferior frontal gyrus, and the insula) [Duffau, 2005a; Lubrano et al., 2010]. Nonetheless, the cortical reorganization of networks involved in object naming is constraint by the subcortical connectivity, so that "a new cortical functional areas" has to be strategically located to exploit subcortical tracts in order to recreate frontal–temporal–parietal domain-specific networks and thereby preserve function [Papagno et al., 2011]. In the present experiment, though we cannot exclude that plasticity driven mechanisms may account for the dissociation between object and action naming sites in GIIG, it is to be stressed that nonoverlapping maps were also observed for high-grade glioma, metastasis, and anaplastic ependymoma. In addition, our patient's population is also heterogeneous in terms of age (i.e., patients ranged in age from 13 to 77 years–median 42). A few maps may have been biased, since four of our patients were in theirs 60s or 70s and there is a controversy whether object names and action names are differentially retrieved with aging [Mackay et al., 2002; Nicholas et al., 1985].

To summarize, though the picture-naming task we used to assess the relative impairment of object–action processing inherently confounds grammatical class with meaning (semantics), tentative interpretations have be drawn about the functional significance of the anatomical loci we focused on, which would favor a cortical distinction between objects and actions based on conceptual/semantic features. However, our experimental data do not allow us to deny that grammatical-class is not a principle of language organization as well.

CONCLUSION

In no region did our brain stimulation mapping study reveal any constant dissociation between the cortical correlates of action and object retrieval. Nonetheless, we observed that aside from a set of areas that were involved in naming both action words (verbs) and objects, some cases showed distinct territories in which stimulation impaired one or the other category-specific task. In these patients, such a category specificity suggests that the tested areas play a critical role in processing either action-related or object-related components of the corresponding lexical-semantic representations. The present findings lend support to a functional specialization so that the left prefrontal/premotor cortex preferentially supports sensorimotor contingencies associated with actions, whereas others in the temporal cortex may preferentially underpin functional properties of manipulable objects per se. Then, in a naming task, the retrieval of semantic and lexical representations linked to objects and actions engage both common and distinct areas in the left inferior frontal cortex. Further investigations are needed to disentangle the respective contributions of action-related semantic processes and morpho-syntactic (grammatical) processes to verb naming effects.

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APPENDIX

The stimuli used in the action/object picture-naming task were taken from the Center for Research in Language-International Picture Naming Project corpus CRL-

IPNP (http://crl.ucsd.edu/experiments/ipnp/1database.html) [Szekely et al., 2005].

We selected the following items: (see the next two pages), which were characterized by their manipulability and nonhomonymy.

Objects/nouns are manipulable if they can be either used or moved by the hand(s) [Rueschemeyer et al. 2010].

Object/noun and action/verb are homonyms if the noun and verb forms are orthographically and phonologically identical [Tranel et al. 2005].

	Nonhomonymous (%)	Homonymous (%)	Nonmanipulable (%)	Manipulable (%)
Objects	92.5	7.5	17.5	82.5
Actions	75	25	25	75

40 objects:

English translation	Object in French	Objects: non functionally manipulable (7/40)	Objects: functionally manipulable (33/40)
Accordion	accordéon		X
Airplane	avion	X	
Alligator	alligator		X
Anchor	ancre		X
Apple	pomme		X
Arrow	flèche		X
Artichoke	artichaut		X
Bottle	bouteille		X
Bed	lit		X
Boat	bateau	X	
Book	livre		X
Bra	soutien-gorge		X
Broom	balai		X
Drill	perceuse		X
Hamburger	hamburger		X
Lemon	citron		X
Light switch	interrupteur		X
Mountain	montagne	X	
Pear	poire		X
Pencil sharpener	taille-crayon		X
Piano	piano		X
Pipe	pipe		X
Pirate	pirate		X
Pool	piscine	X	
Pyramid	pyramide	X	
Road	route	X	
Saw	scie		X
Screw	vis		X
Stethoscope	stéthoscope		X
Submarine	sous-marin	X	
Table	table		X
Tent	tente		X
Tie	cravatte		X
Vase	vase		X
Watch	montre		X
Whistle	sifflet		X
Window	fenêtre		X
Glass	verre		X
Witch	sorcière		X
Zipper	fermeture-éclair		X

40 objects:

English translation	Object in French	Objects: nonhomonymous (37/40)	Objects: homonymous (3/40)
Accordion	accordéon	X	
Airplane	avion	X	
Alligator	alligator	X	
Anchor	ancre	X	
Apple	pomme		
Arrow	flèche		
Artichoke	artichaut		
Bottle	bouteille		
Bed	lit	X	
Boat	bateau	X	
Book	livre	X	
Bra	soutien-gorge	X	
Broom	balai		X
Drill	perceuse	X	
Hamburger	hamburger	X	
Lemon	citron	X	
Light switch	interrupteur	X	
Mountain	montagne	X	
Pear	poire	X	
Pencil sharpener	taille-crayon	X	
Piano	piano	X	
Pipe	pipe	X	
Pirate	pirate	X	
Pool	piscine	X	
Pyramid	pyramide	X	
Road	route	X	
Saw	scie		X
Screw	vis		X
Stethoscope	stéthoscope	X	
Submarine	sous-marin	X	
Table	table	X	
Tent	tente	X	
Tie	cravatte	X	
Vase	vase	X	
Watch	montre	X	
Whistle	sifflet	X	
Window	fenêtre	X	
Glass	verre	X	
Witch	sorcière	X	
Zipper	fermeture-éclair	X	

40 actions:

English translation	Action verb in French	Verbs: nonhomonymous (30/40)	Verbs: homonymous (10/40)
To bark	(aboyer)	X	
To brush	(brosser)		X
To pay	(payer)		X
To carry	(porter)	X	
To comb	(peigner)		X
To drill	(percer)	X	
To fall	(tomber)	X	
To fish	(pêcher)		X
To iron	(repasser)	X	
To juggle	(jongler)	X	
To jump	(sauter)	X	
To knit	(tricoter)	X	
To laugh	(rire)	X	
To lift	(soulever)	X	
To light	(éclairer)	X	
To mail	(poster)		X
To make	(faire)	X	
To operate	(opérer)	X	
To peel	(éplucher)	X	
To pet	(caresser)		X
To push	(pousser)	X	
To fix	(réparer)	X	
To row	(ramer)		X
To salute	(saluer)		X
To punish	(punir)	X	
To shower	(doucher)		X
To sing	(chanter)	X	
To cut	(cut)		X
To smoke	(fumer)	X	
To squeeze	(presser)	X	
To tear	(déchirer)	X	
To talk	(parler)	X	
To throw	(jeter)	X	
To type	(écrire à la machine)	X	
To vacuum	(passer l'aspirateur/ aspirer)	X	
To watch	(regarder)	X	
To whistle	(siffler)	X	
To win	(gagner)	X	
To wash	(laver)	X	
To write	(écrire)	X	

40 actions:

English translation	Action verb in French	Verbs: manipulable (30/40)	Verbs: nonmanipulable (10/40)
To bark	(aboyer)		X
To brush	(brosser)	X	
To pay	(payer)	X	
To carry	(porter)	X	
To comb	(peigner)	X	
To drill	(percer)	X	
To fall	(tomber)		X
To fish	(pêcher)	X	
To iron	(repasser)	X	
To juggle	(jongler)	X	
To jump	(sauter)		X
To knit	(tricoter)	X	
To laugh	(rire)		X
To lift	(soulever)	X	
To light	(allumer)	X	
To mail	(poster)	X	
To make	(faire)	X	
To operate	(opérer)	X	
To peel	(éplucher)	X	
To pet	(caresser)	X	
To push	(pousser)	X	
To fix	(réparer)	X	
To row	(ramer)	X	
To salute	(saluer)	X	
To punish	(punir)		X
To shower	(doucher)	X	
To sing	(chanter)		X
To cut	(cut)	X	
To smoke	(fumer)	X	
To squeeze	(presser)	X	
To tear	(déchirer)	X	
To talk	(parler)		X
To throw	(jeter)	X	
To type	(écrire à la machine)	X	
To vacuum	(passer l'aspirateur/ aspirer)	X	
To watch	(regarder)		X
To whistle	(siffler)		X
To win	(gagner)		X
To wash	(laver)	X	
To write	(écrire)	X	